ELECTROSTATICALLY OPERATED MICRO-OPTICAL DEVICES AND METHOD FOR MANUFACTURING THEREOF

BACKGROUND OF THE INVENTION

1. Field of the invention

This invention is related to electrostatically operated micro-optical devices and method of manufacturing such devices.

2. Description of the prior art

Considerable interest has recently been shown in optical microelectromechanical systems (optical MEMS) based on comb drives using an electrostatic actuation scheme. Combining the comb-drive actuator with the silicon-on-insulator (SOI) and deep-reactive-ion-etching (DRIE) process, many MEMS based components have been demonstrated such as optical switch, variable optical attenuator (VOA), and Fourier transform spectrometer (FTS), etc. It can be seen that, for example, W. Noell, et al., "Applications of SOI-Based Optical MEMS", IEEE J. on Selected Topics in Quantum Electronics, Vol. 8, No. 1, Jan/Feb 2002, pp.148-154; C. Marxer, et al., " A Variable Optical Attenuator Based on Silicon Micromechanics", IEEE Photonics Technol. Lett., Vol. 11, No. 2, 1999, pp. 233-235; C. Marxer and N.F. de Rooij, " Micro-Opto-Mechanical 2x2 Switch for Single-Mode Fibers Based

on Plasma-Etched Silicon Mirror and Electrostatic Actuation", IEEE J. of Lightwave Technology, vol. 17, No. 1, 1999, pp.2-8; W. -H. Juan and S. W. Pang, " High-Aspect-Ratio Si Vertical Micromirror Arrays for Optical Switching", IEEE J. Microelectromechanical Systems Vol. 7, No. 2, 1998, pp.207-213. Prior arts of U.S. Pat. No. 6315462, " Fiber Optic Circuit Switch and A Process for Its Production," O. Anthamatten and C. Marxer; and U.S. Pat. No. 6229640, " Microelectromechanical Optical Switch and Method of Manufacture Thereof," N. Zhang have described the utilization of DRIE and wet etching release process technologies to construct the optical switch devices from SOI wafer, or bonded silicon wafers. Such disclosed micro-optical devices comprise a high-aspect-ratio micro-mirror with vertical sidewall and an electrostatic comb drive actuator for controlling the position of micro-mirror. The common comb drive actuator includes a stationary comb finger electrode, and a movable comb finger electrode connected with the movable part, i.e., the micro-mirror in this case, via a suspended spring. This mentioned suspended spring is anchored on to substrate at one end. The electrostatic force for moving the micro-mirror can be generated by applying voltage to comb drive actuator. The restoration force generated by the deformed spring will pull the actuated micro-mirror returning to the initial position. Regarding to the application of optical switch, micro-mirror can be moved from the initial off-state (light transmission state) to the actuated on-state (light reflection state, i.e., switching) via applying voltage to comb drive actuator. On the other hand, the light attenuation range for VOA application is determined in terms of the in-plane position of Si micro-mirror, where this in-plane position is controlled via force balance between electrostatic force and spring force. Thereby it can control

relative amount of attenuation by blocking part of light beams.

It is important for micro-optical devices like optical switch and VOA devices to be operated at low electrical power consumption in order to keep the overall power consumption of the whole optical network system as low as possible. As a result, the electrostatic actuation scheme offered by MEMS actuator shows no power consumption and is the best candidate for optical switch and VOA applications, because there no electrical current flows through electrodes. However, a continuously applied electrical load on MEMS actuator is necessary to hold the micromirror of optical switch staying at the on-state, because we need the force generated by MEMS actuator to balance the restoring force from spring. Therefore, mechanically-bistable mechanisms, i.e., latch mechanism, providing two relative positions that are both mechanically stable is desirable for optical switch to maintain at on-state without power consumption. Prior art of U.S. Pat. No. 6303885, " Bi-stable Micro Switch" B. P. Hichwa, C. Marxer, and M. Gale has disclosed a latched optical switch using buckled-beam with the arch-shaped leaf spring geometry driven by a bi-directional movable electrostatic comb actuator. Additionally, prior art of U.S. Pat. No. 6549107, " Latching Mechanism for MEMS Actuator and Method of Fabrication" M. Lim, R. Fan, and L. Que has disclosed the other kind of latch mechanism for optical switch has been realized by using gripper to clamp the switch at one position.

It is also important for micro-optical devices like optical switch and VOA devices to have low insertion loss, low polarization dependent loss, and low back reflection loss for practical applications. Combining the MEMS

elements with micro-optics provides optical switch and VOA devices a free-space light path design approach. This is a key way to make the light beam coming from input fiber become collimated beam shape thereby to gain in better optical performances. The larger collimated beam size, from several tens to hundreds of micrometers, will make better optical performance, and make the acceptable alignment tolerance higher. However, it will also lead to a requirement that the corresponding MEMS actuator has to be able to provide enough displacement to let micromirror fully block or reflect the incoming light beam. In the conventional design of electrostatic comb-drive actuator, the maximum static displacement of comb actuator is limited by the side sticking effect of comb fingers. The tiny deviations of comb finger and gap width will cause the unbalanced force of both sides of finger electrode, and such deviation is easily induced by microfabrication process. The unbalanced force of both sides of finger electrode is the major contribution factor to the side sticking effect. How to design and make a comb drive actuator that is more robust to the process induced deviation and provides longer displacement is very attractive to industrial pratical uses. There are two fundamental approaches to realize a comb drive actuator with such capability, one is making the spring perpendicular to mirror moving direction as stiffer as possible, and the second

one is making the force output of comb drive as higher as better.

The present invention provides micro-optical devices with electrostatic microactuator for optical switch and variable optical attenuator devices applications, and its relative manufacturing process techniques. According to aforementioned functional requirements for applications of optical switch and variable optical attenuator devices, the desirable design of an electrostatic microactuator should include large displacement, large force output, latch mechanism, design-in mechanisms to gain in better optical performance, and design-in processes and device structures to gain in better production yield, and so on. Therefore, the present invention discloses an electrostatic microactuator, and related structures and manufacturing processes especially emphasizing in fulfilling such design requirements.

SUMMARY OF THE INVENTION

The present invention has been made in view of the above micro-optical device function requirements, and it is an object of present invention to provide micro-optical devices using an electrostatic microactuator having new spring designs to overcome side instability and exhibit enlarged displacement, and to

provide micro-optical devices using an electrostatic microactuator having new designs of comb finger electrode shapes to generate larger force output, and to provide a new optical light path design in conjunction with said electrostatic microactuator to render the made micro-optical devices exhibiting better optical performance, and to provide micro-optical devices using an electrostatic comb drive actuator having new latch mechanism to maintain the micro-optical device at particular state without additional electrical load on the electrostatic microactuator, and to provide process techniques to manufacture the micro-optical devices with said electrostatic microactuator in a mass production manner with higher yield.

The micro-optical devices according to the present invention comprise a set of movable comb finger electrodes connected with a movable suspended micro-mirror via a shuttle beam, a set of stationary comb finger electrodes, and a set of suspended springs. One end of this set of suspended springs is connected with the movable comb and micro-mirror through the shuttle beam, while the other end is connected with a fixed anchor regarding to the substrate. The force generated by electrostatic comb drive actuator upon various values of the applied voltage will bend the spring and induce displacement of said mirror and shuttle beam. The light attenuation is achieved in analog control manner

regarding to mirror position via the force balance between bended spring and functioned comb drive actuator. Moreover, regarding to the case of buckled spring, the spring is arched toward on direction parallel along with the moving direction. The existing spring force exerts on shuttle beam to hold said mirror at one of the bi-stable state. The mirror and shuttle will start to move when the buckled spring being deflected into opposite direction with deflection equivalent to 133% initial buckled deflection due to the generated electrostatic force against to the existing buckled spring force. <u>(The value of 133% could be found in the reference of US patent in application "2003/0029705A1")</u> Thereafter, the mirror and shuttle beam will move to the other position of the bi-stable state. Combining with fiber optics, the micro-optical devices using electrostatic comb drive actuator and buckled spring can be operated as the optical switch devices.

In the preferred embodiments, the suspended spring beam of said micro-optical devices can be thinned by dry etching technology, therefore spring thickness in the perpendicular out-of-plane direction to substrate is thicker than the thickness of comb drive finger electrodes. As a result, the spring become soft in moving direction, and become stiffer in the perpendicular in-plane direction to the moving direction.

According to the invention, many ways can be provided to make said spring of said micro-optical device and its comb drive actuator to become compressive beam when said comb drive actuator start to move. Thereby the spring constant in the perpendicular in-plane direction to the moving direction will increase as the in-plane displacement increasing in moving direction. As a result, micro-optical devices using this kind of comb drive actuator are suitable for device designs and applications need large mirror displacement. These ways include but not limited to the following disclosed approaches: A comb drive actuator comprising four normal folded-beam springs in symmetric layout is disclosed in present invention; A comb drive actuator comprising four compressive folded-beam springs in symmetric layout is disclosed; A comb drive actuator comprising a pair of normal folded-beam springs and a pair of compressive folded-beam springs in symmetric layout is invented; A comb drive actuator comprising a pair of normal folded-beam springs with an U-shaped-bridge joint and a pair of compressive folded-beam springs located in a symmetric layout is invented too.

In other embodiments, the finger electrode shape of said comb drive actuator of said micro-optical device is a kind of shape with an oblique angle to enlarge the force output from said comb drive actuator, thereby the

micro-optical devices using this kind of comb drive actuator are suitable for device designs and applications need large actuation force.

In accordance with other aspect of the present invention, an off-axis light path layout design enabling less coupled back-return-loss for said micro-optical devices is invented for analogically controlling the light attenuation.

In accordance with other aspect of the present invention, a clip type latch using friction force or electrostatic force mechanism is invented for said micro-optical devices to maintain the status of said micro-optical devices at certain condition without power consumption.

According to the present invention, many ways can be provided to make the mirror surface smoothness of said micro-optical devices in a mass production manner with higher production yield, including but not limited to applying the silicon etching solution to reduce the surface roughness; adopting the (110) oriented silicon substrate in conjunction with post-etching in the silicon etching solution; and oxidizing the mirror surface after the mirror side wall is formed.

According to the present invention, many ways can be provided to make the packaging process of said micro-optical devices in a mass production manner with higher production yield, including but not limited to lid capping on the substrate to protect the fragile MEMS elements; making flow channels and trenches on the substrate to avoid the movable and suspended MEMS elements being attacked by the sealing and assembling materials like glues, epoxy, solders, etc; and dicing the devices form substrates, then became discrete dies when the MEMS elements have been protected by lids.

The above and other objects, features and advantages of the present

invention will become more apparent from the following detailed description taken in conjunction with the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram of the micro-optical device comprising comb drive actuator with folded-beam springs in axial type variable optical attenuation configuration in accordance with the prior art.

Fig. 2 is a schematic diagram of the micro-optical device comprising comb drive actuator with folded-beam springs in 2x2 optical switch configuration in accordance with the prior art.

Fig. 3a and **3b** are the schematic diagrams of the micro-optical device comprising comb drive actuator with thinned springs of the present invention.

Fig. 4a through **4f** are the cross-sectional views of the micro-optical device comprising comb drive actuator with folded-beam springs with respect to the manufacturing procedure according to the present invention.

Fig. 5 shows the measured and simulated results of displacement vs. applied voltage for a comb drive actuator with two- and three-folded normal springs, and thinned springs of the present invention.

Fig. 6 is the top view of the micro-optical device comprising comb drive

actuator with symmetric normal folded-beam springs of the present invention.

Fig. 7 is the top view of the micro-optical device comprising comb drive actuator with symmetric compressive folded-beam springs of the present invention.

Fig. 8a and **8b** are the top views of the micro-optical device comprising comb drive actuator with asymmetric spring design that is normal folded-beam springs on one-side and compressive folded-beam springs on the other side; asymmetric spring design that is normal folded-beam springs with U-shaped-bridge joint on one-side and compressive folded-beam springs on the other side, respectively.

Fig. 9 shows the curves of spring constant k_y along with the direction perpendicular to the moving direction of symmetric parallel spring, symmetric compressive spring, asymmetric hybrid spring, and asymmetric hybrid springs with U-shaped-bridge joint for comb drive actuator and stability criteria $\mathbf{k_{ey}}$ versus various actuation displacement of comb drive actuator of the present invention.

Fig. 10a and **10b** are the simplified top views of finger electrode shape drawing of conventional comb drive actuator, and finger electrode shape with oblique-angle shape of the present invention.

Fig. 11a shows the light path based on using reflective movable micro-mirror to change the transmission path with respect to reflected light signals.

Fig. 11b is a multiple reflected light path for variable optical attenuation and optical switching applications realized by using a plurality of said reflective micro-mirrors of the present invention.

Fig. 12a and b are simplified top views of a clip type latch based on using friction force and / or electrostatic force to clamp the movable structure for present invention disclosed micro-optical devices disclosed in the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be constructed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Matched with corresponding drawings, the preferable embodiments of the invention are presented as following and hope they will benefit your esteemed reviewing committee members in reviewing this patent application favorably.

Referring now to **Fig. 1** and **2**, the simplified side view and top view drawings of a shutter type VOA and crossbar optical switch are disclosed by prior arts, see for example, W. Noell, et al., "Applications of SOI-Based Optical MEMS", IEEE J. on Selected Topics in Quantum Electronics, Vol. 8, No. 1, Jan/Feb 2002, pp.148-154; C. Marxer, et al., " A Variable Optical Attenuator Based on Silicon Micromechanics", IEEE Photonics Technol. Lett., Vol. 11, No. 2, 1999, pp. 233-235; C. Marxer and N.F. de Rooij, " Micro-Opto-Mechanical 2x2 Switch for Single-Mode Fibers Based on Plasma-Etched Silicon Mirror

and Electrostatic Actuation", IEEE J. of Lightwave Technology, vol. 17, No. 1, 1999, pp.2-8; W. -H. Juan and S. W. Pang, " High-Aspect-Ratio Si Vertical Micromirror Arrays for Optical Switching", IEEE J. Microelectromechanical Systems Vol. 7, No. 2, 1998, pp.207-213. These disclosed micro-optical devices for VOA and optical switch applications may be made in accordance with various known fabrication processes. In a particular process, the micro-optical devices 100 are made on substrates 110 such as, the commercially available silicon-on-insulator (SOI) wafers. The SOI wafer includes a single crystal silicon device layer on a single crystal silicon handle wafer with a normally less than 2 micrometers thick SiO_2 insulator layer. The micro-optical devices 100 comprise a reflective movable micro-mirror 113 on a shuttle beam 121, a set of suspended springs 123a, 123b connected with the shuttle beam 121, a set of movable comb drive electrodes 122 that is connected with movable shuttle beam 121 and said suspended springs 123a, 123b move toward a set of stationary comb drive electrodes 117 a, b, c due to the electrostatic force between said two sets of comb drive electrodes when the electrical load is applied to the comb drive actuator, and a set of fiber optics 111, 112 for handling the input and output optical signals 114, 115, respectively. These features and microstructures of micro-optical devices 100 are formed in

the device layer of SOI wafer via using the deep-reactive-ion-etching (DRIE) process, then a hydrofluoric acid (HF) etch process is used to remove the oxide underneath portions of the micro-optical device movable in relation to the base or substrate, such as the micro-mirror 113, shuttle beam 121,suspended springs 123a, 123b, movable comb drive electrodes 122, etc. Process induced feature size deviations may lead to the side instability regarding to the electrostatic force unbalance between electrode fingers 119 of movable comb drive electrodes 122 and electrode fingers 118 of stationary comb drive electrodes 117 a, b, c. The misalignment and improper treatment during the photolithography, and the side wall etching effect during the DRIE process may cause the phenomena of that comb feature size deviated from the designed and planed layout.

With respect to the operation of said micro-optical devices 100 for VOA application, the micro-mirror 113 located in between the spacing of transmission fiber 111 and reception fiber 112, and the light propagation path is along with the same axis of these two fibers i.e., the axial type configuration. The light is attenuated in terms of the percentage of transmission light beam being blocked by the micro-mirror 113 regarding to the position of micro-mirror 113. The position of micro-mirror 113 can be further adjusted by

a comb drive actuator via shuttle beam 121. On the other hand, a crossbar optical switch can be formed in the same way and with the outlooks like the one shown in Fig. 1. The operation of said micro-optical devices 100 for crossbar optical switch application is depicted as the simplified drawing shown in Fig. 2. The micro-mirror 214 is located in the center of cross lines of light paths 215 of transmission fiber of channel one 211a to reception fiber of channel three 212a, and transmission fiber of channel two 211b to reception fiber of channel four 212b. According to the position of reflective micro-mirror 214 controlled by the comb drive actuator 213, the incoming optical signals from channel one 211a can transmit forward to the output channel three 212a, while the incoming optical signals from channel one 211b can transmit forward to the output channel three 212b, thereby said optical switch is operated at its transmission state. Moreover, the incoming optical signals from channel one 211a can transmit toward the micro-mirror 214 and being reflected forward to the output channel three 212b, while the incoming optical signals from channel one 211b can transmit toward the micro-mirror 214 and being reflected forward to the output channel three 212a, i.e., the switching state or reflection state.

The first embodiment

Again, due to the side instability issue, and requirement of longer traveling distance of micro-mirror 214, i.e., the displacement of comb drive actuator, we proposed a micro-optical device 310 using electrostatic comb drive actuators having thinned spring structure 312 as shown in Fig. 3. Let us go through the fundamental physics with respect to the mechanics of comb drive actuator. Fig. 3 shows the well-adopted comb drive actuator design with folded-beam spring 311. Such design has been reported to show increased displacement under the same actuation voltage comparing with traditional spring design, since the spring constant in and perpendicular to moving direction can become smaller and larger, respectively. (See for example, V. P. Jaecklin, C. Linder, N. F. de Rooij, and J. M. Moret, " Micromechanical Comb Actuators with Low Driving Voltage," J. Micromech. Microeng., Vol. 2, 1992, pp. 250-255; R. Legtenberg, A. W. Groeneveld, and M. Elwenspoek, " Comb-drive Actuators for Large Displacements," J. Micromech. Microeng., Vol. 6, 1996, pp. 320-329.) Therefore the maximum displacement of comb with folded-beam spring 311 can be increased without the side snapping effect of comb fingers when electrostatic force is larger than spring force. Comb drive actuator design is based on force equilibrium between electrostatic force and spring force, as shown in Fig. 3. Thus the static actuation displacement can be generally expressed as:

$$\Delta x = \frac{N \cdot \varepsilon \cdot t_e}{k_x \cdot g} \cdot V^2 \qquad (1)$$

,where N is the number of comb electrode; ε is the permittivity constant of air; t_e is the comb electrode thickness; g is the comb electrode gap; V is the driving voltage; k_x is spring constant in moving direction and denoted as x-direction; Δx is the actuating displacement.

According to that the 2-folded beam spring can provide high stiffness ratio, i.e., the spring constant in lateral direction (defined as y-direction) over the spring constant in moving direction, most of comb-drive actuators adopt such 2-folded beam type of spring for various applications up to date. Each 2-folded beam is a combination of two clamped-guided beams, in the other words it consists of two sets of parallel cantilever beams in series, as shown in Fig. 3. In order to reduce the driving voltage demanded for large travel distance, a more flexible spring, i.e., 3-folded and 4-folded beam spring, is disclosed by present inventors in the literatures (Chihchung Chen, Chengkuo Lee, Yenjyh Lai, and Wen-Chih Chen, "Study of Lateral Comb Drive Actuator with Large Displacement and Low Actuation Voltage," *Proc. of Microprocesses and Nanotechnology 2002,* pp.304-305, Tokyo, Japan, Nov. 6-8, 2002, IEEE Catalog No. 02EX589.; and Chihchung Chen, Chengkuo Lee, Yenjyh Lai, and Wen-Chih Chen, "Development and Application of Lateral Comb-drive Actuator," Jpn. J. Appl. Phys. Vol. 42, Part.1, No. 6B, 2003, pp.4059-4062) and has been disclosed by U.S. Pat. 6315462, "Fiber Optic Circuit Switch and A Process for Its Production," O. Anthamatten, and C. Marxer, Nov. 13, 2001. Similar to the 2-folded beam spring, this 3-folded or 4-folded beam spring consist of two clamped-guided beams and bended three-folds or four-folds. It means that each clamped-guided beam consists three serious parallel cantilever beams. Assume the spring constant in equation (2) and (3) of each cantilever beam is k. Thus the equivalent spring constant of 2-folded beam spring and 3-folded beam spring is equivalent to $2k$ and $4/3k$, respectively, which can be derived from k and expressed as

2-folded spring constant $k''_x = 2k = \frac{2Et_sW^3}{L^3}$ (2)

3-folded spring constant

$$k_x''' = (4/3)k = \frac{4Et_sW^3}{3L^3} \qquad (3)$$

, where E is the Young's modules, t_s is the spring thickness; W is the beam width of a clamped-guided beam of a folded-beam spring; L is the folded spring beam length.

Hence, for the same displacement, driving voltage of 3-folded beam spring is smaller than the voltage of 2-folded beam spring, i.e., in the ratio of $\sqrt{2/3}$. Besides, according to eqs. (1) ~ (3), we may also realize that the comb drive displacement is in proportion to the ratio of t_e/t_s under a fixed applied voltage. The ratio of t_e/t_s means the thickness ratio of comb finger electrode to comb spring, where this ratio equals one in general case. However, it gives us a hint that displacement can be enlarged under the same applied voltage, if the spring thickness is thinner than comb electrode thickness. To the best knowledge of inventors', there is no reported data and literature about comb drive of stepped-structure between electrode finger and spring.

To make the folded-beam spring 311 become thinner as thinned folded-beam spring 312 shown in Fig. 3, we can apply the process shown in Fig. 4 to fabricate the micro-optical device 310 with thinned spring structure 312. After the first lithography step, SiO_2 hard mask 412 is patterned to be the shapes of the comb electrodes, shutter, and anchors on silicon device layer of SOI wafer 411 (Fig. 4a ~ 4b). The photo resist (PR) mask 416 is defined thereafter to be the shape of folded-beam spring (Fig. 4c). By using deep reactive ion etching (DRIE) to etch this SOI wafer with said SiO_2 hard mask 412 and photo resist mask 416 on surface, the PR mask will be fully etched away after silicon of no mask area being etched down to certain depth. Then

the area of folded-beam spring begins to be etched. Since the Si/PR etching selectivity is approximately 10 ~ 40 during typical DRIE process. The DRIE process is done when the insulation SiO_2 layer underneath the silicon device layer is reached during the etching process (Fig. 4e). The movable comb fingers, shutter, and suspended thinned spring are eventually released by HF wet etching (Fig. 4f). A step height between folded-beam spring and comb finger electrodes can be made to form a micro-optical device 310 with stepped structures.

To further explain and prove our invention, We made comb drives of 4 types of springs, they were comb drives of 3-folded normal spring, 3-folded thinned spring, 2-folded normal spring, and 2-folded thinned spring. The related geometric parameters of these springs are spring length of 800μm, spring width of 2.3 μm, spring thickness of 92μm, comb finger gap of 4μm, comb finger number of 100, comb finger overlap of 20μm, and comb finger thickness of 45μm. Comparing measured data with the simulated curves of displacement versus square of applied voltage as shown in Fig. 5, the 3-folded thinned spring comb drive can be actuated by a relatively lowest driving voltage. This result points out that the comb drive of 3-folded thinned spring exhibits the best-optimized performance, i.e., the larger displacement under the same applied voltage, and the longest displacement without happening side sticking of comb finger electrodes. It proved our invention may lead to comb drive actuators have higher stiffness in perpendicular direction, i.e., the y-direction, to moving direction and lower spring force in the moving direction i.e., the x-direction. Without making springs of longer length, it means larger occupation area and lower process yield, we can have voltage reduction by just

making the spring thinner. Beside, according to present process design, this thinned spring structure is defined and patterned by one mask only. It means no physical parameter deviation occurred due to the process, like misalignment induced variation of spring width, etc. The above experimental results have been disclosed by inventors in these papers (Chihchung Chen, Chengkuo Lee, Yenjyh Lai, and Wen-Chih Chen, "Study of Lateral Comb Drive Actuator with Large Displacement and Low Actuation Voltage," *Proc. of Microprocesses and Nanotechnology 2002,* pp.304-305, Tokyo, Japan, Nov. 6-8, 2002, IEEE Catalog No. 02EX589.; and Chihchung Chen, Chengkuo Lee, Yenjyh Lai, and Wen-Chih Chen, "Development and Application of Lateral Comb-drive Actuator," Jpn. J. Appl. Phys. Vol. 42, Part.1, No. 6B, 2003, pp.4059-4062).

The second embodiment

In according to another aspect of our invention, the micro-optical devices 100 shown in Fig. 1 or micro-optical devices 310 shown in Fig. 3 can be modified into the layout configuration shown in Fig. 6. To further reduce the instability influence from the moment contributed by the lateral electrostatic force of comb electrodes, all the spring anchors are assigned symmetrically at both sides of comb electrodes. By using such symmetric layout in conjunction with our spring thinning approach, we are able to make the comb drive actuator exhibit enlarged displacement and robustness to instability.

On the other hand, several prior arts have disclosed a factor that spring constant of the suspended spring in the y-direction of comb drive actuator will be increased along with the increased displacement in the x-direction when this

spring become compressive state along with the y-direction at the beginning, i.e., no displacement state, or no actuation state. (See for example, U.S. Pat. 5998906, "Electrostatic Microactuator and Method for Use Thereof," John H. Jerman, John D. Grade, and Joseph D. Drake, Dec. 7, 1999; Guangya Zhou and Philip Dowd, " Tilted Folded-beam Suspension for Extending The Stable Travel Range of Comb-drive Actuators," Journal of Micromech. and Microeng. Vol.13, 2003, pp. 178-183; " Design of Large Deflection Electrostatic Actuator," Journal of Microelectromechanical Systems Vol.12, No.3, 2003, pp.335-343.) Thus the compressive spring can maintain higher stiffness in the y-direction than the conventional normal spring; that is, the maximum displacement in x-direction can be enlarged by utilizing the compressive spring instead. In order to further explain the details of our present inventions, we make the definitions and background explanations of parameters regarding to mechanics of comb drive actuator first. As shown in **Fig. 3**, it explains the simplified relation between movable and stationary combs. When a driving voltage is applied across the comb set, the electrostatic force along the moving direction (x-direction) is defined as:

$$F_{ex} = \frac{N \cdot \varepsilon \cdot t_e}{g} \cdot V^2 \qquad (4)$$

where N is the number of comb electrode fingers; ε is the permittivity constant

of air; t_e is the comb electrode thickness; g is the comb electrode gap; V is the driving voltage. Besides, the static actuation displacement is generally defined by equation 1. While the electrostatic force along the in-plane direction perpendicular to moving direction (y-direction) is given by:

$$F_{ey} = \frac{N \cdot \varepsilon \cdot t_e \cdot l}{2 \cdot (g-y)^2} \cdot V^2 - \frac{N \cdot \varepsilon \cdot t_e \cdot l}{2 \cdot (g+y)^2} \cdot V^2 \qquad (5)$$

where l is the initial overlap of the comb electrodes of two sides, and y is the shift distance of movable comb finger from central axis between two stationary comb fingers. We further interpret the stability criteria of equivalent spring constant in y-direction, i.e., k_{ey}, by considering the deviation Δ in y direction shown in **Fig. 3** as:

$$k_{ey} = \left.\frac{\partial F_{ey}}{\partial y}\right|_{y=\Delta} = N \cdot \varepsilon \cdot t_e \cdot l \cdot V^2 \cdot \alpha \qquad (6)$$

$$\alpha = \left(\frac{1}{(g-\Delta)^3} + \frac{1}{(g+\Delta)^3}\right) \qquad (7)$$

where Δ is the variation tolerance of movable comb finger in y-direction. According to our experiment, the variation tolerance is mainly dominated by the process variation. If k_y is larger than k_{ey}, then the comb can be operated without any side sticking influence; The movable comb fingers will become

instable in y-direction when k_y is less than k_{ey}. Therefore, the maximum stable traveling distance Δx_{max} appears when k_y is equal to k_{ey}, and can also be derived as:

$$\Delta_{x\max} = -\frac{L_0}{2} + \sqrt{\frac{L_0^{\ 2}}{4} + \frac{1}{g \cdot \alpha} \cdot \frac{k_y}{k_x}} \qquad (8)$$

Obviously the maximum traveling distance will be increased, when k_x is decreased and/or k_y is increased. The k_y of conventional comb-drive design, i.e., using the normal folded-beam flexure spring, is decreasing as the actuated displacement increasing, in the mean time the k_e sustains approximately constant. At this situation, the maximum traveling distance is constrained by the side instability effect.

With the background understanding, in order to compare the difference regarding to compressive and normal springs we propose three new designs of comb drive actuators. Similar to the symmetric normal folded-beam springs 615a to 615d on both sides as shown in Fig. 6, we design new comb drives with symmetric compressive folded-beam springs 715a to 715d on both sides, as shown in Fig. 7, and new comb drives with asymmetric folded-beam springs layout on both sides, but one is the compressive spring and the other is the normal spring, as shown in Fig. 8a. Based on the analytical model, and FEM analysis results via ANSYS, we may derive the curves of k_y and k_{ey} versus the travel distance in x-direction, as shown in Fig. 9. It presents the k_y of comb drive with symmetric parallel folded-beams spring decreased rapidly and the

value of k_y coincides with the k_{ey} at 32 μm travel distance. Regarding to the comb drive with compressive folded-beams springs, in spite of that the k_y of comb drive with a pair of compressive springs is increased as spring being compressed, the k_y still coincide with the k_{ey} at 18 μm displacement. Because the initial k_y of this type comb is too small. To further enhance the lateral stiffness in y-direction of comb-drive with compressive beam spring design over initial actuation period, one pair of the compressive beam springs is replaced by a pair of normal folded-beam spring, and then this is denoted as a comb drive with asymmetric hybrid springs, as shown in Fig. 8a. Therefore the micro-optical device using this comb drive actuator comprises a pair of normal folded-beam spring 816a and 816b on one side, and a pair of compressive beam springs 815a and 815b on the other side. However, this third type comb drive actuator exhibits a decreased k_y regarding to increment of x-directional displacement. To strengthen the lateral stiffness of this asymmetric spring comb again, we proposed an U-shaped-bridge joint 862 to connect the pair of parallel normal folded-beams springs to enable a new comb drive actuator based on asymmetric hybrid springs with U-shaped-bridge joint 862 comprises a pair of normal folded-beam spring 856a and 856b with an U-shaped-bridge joint 862 on one side, and a pair of compressive beam springs 855a and 855b on the other side, as shown in Fig. 8b. As shown in Fig.9, similarly, the initial k_y of this type has been apparently promoted by such modification, the k_y keeps increasing as the displacement increasing as the same trend observed in the case of four compressive folded-beam springs. As a result, the k_y of the asymmetric comb drive actuator with U-shaped-bridge joint 862 meets with the k_e at x-directional travel distance of 58μm approximately. By using our

innovative design, we are able to increase the maximum static displacement performance about 81% in this case.

These data point out a factor that our new asymmetric hybrid springs with U-shaped-bridge joint design will provide comb drive actuator with maximum stable displacement and corresponding maximum force output in moving direction than the normal folded-beams design. Part of this invention is going to be disclosed in the coming conference Eurosensors XVII, 17th European Conf. On Solid-State Transducers, Guimarães, Portugal, Sept. 21-24, 2003 in the title of "Development of Comb Drive with New Compressive Suspension Spring for Large Static Displacement and Continuous Motion Applications," by Chihchung Chen, Chengkuo Lee.

Based on the detailed description of our invention, the micro-optical device based on the layout and design using said aforementioned approach to make the micro-mirror can perform large displacement to fulfill diversified requirements regarding to broaden applications.

The third embodiment

In according to the other aspect of our invention, we proposed micro-optical devices using comb drive actuator 1050 with comb finger electrodes of a shape with oblique angle 1051, 1052, as shown in Fig. 10b. Thereby the force output from said comb drive actuator is enlarged based on this approach. Basically the generated electrostatic force from the comb drive actuator is contributed by the electrostatic field between the two comb finger electrodes. Comparing to the electrode shape of conventional comb finger 1001 and 1002 as shown in Fig. 10a, the major field line is aligned much closed to

the moving locus, which means better energy coupling efficiency can be obtained. Therefore, under the same input voltage, the force generated by comb drive of oblique shape comb finger electrode (1050) is larger than the conventional comb drive actuator 1000. The relative experimental results have been disclosed by the following literatures, see for example, M. A. Rosa, S. Dimitrijev, and H. B. Harrison, "Enhanced electronic force generation capability of angled comb finger design used in electrostatic comb-drive actuators," Electronics Letters, 1998, Vol.34, No. 18, pp.1787~1788; J. Hsieh, C.-C. Chu, and W. Fang, "On the driving mechanism design for large amplitude electrostatic actuation," Proceedings of 2001 **ASME** International Mechanical Engineering Congress and Exposition, paper number of **IMECE2001/MEMS**-23804, Nov. 11~16, 2001, New York, USA. These publications have proven the basic idea regarding to comb drive of oblique shape comb finger electrode. To the best knowledge of inventors', there is no published works regarding to the micro-optical devices using comb drive actuator with comb finger electrode of oblique shape. Thereby micro-optical devices using this new comb drive actuator are suitable for device designs and applications need large actuation force. In conjunction with spring with higher stiffness, the micro-optical devices using this new comb drive actuator can generate larger actuation force against to the spring force ad side instability effect, thereby reaching larger x-directional displacement.

<u>The fourth embodiment</u>

Referring to the common configuration of most reported VOA device, there is a micro-shutter located in between the spacing of transmission and reception

fibers, and the light propagation path is along with the same axis of these two fiber, i.e., the axial type configuration. The light is attenuated in terms of the percentage of transmission light beam being blocked by shutter with respect to position of shutter, where the position of shutter is electrically controlled by micro-actuators. To get the insertion loss as small as possible, the spacing between two fiber ends is arranged as small as possible. Nevertheless, the back-return loss is hard to be diminished to less than -50dB, using a micro-mirror to reflect a portion of input optical signals and making the reflected portion of input optical signals to be coupled into output ports is a good way to reduce the back-return loss with respect to the back-reflected light from micro-mirror to input port. Based on using this reflective micro-mirror to perform the light attenuation task, there is one approach that is adopting a flat reflective micro-mirror and out-of-plane light path configuration, (See for example, K. C. Robinson, US Pat. 6137941, " Variable Optical Attenuator,"; and K. Isamoto, K. Kato, A. Morosawa, C. Chong, H. Fujita, and H. Toshiyoshi, " Micromechanical VOA design for high shock-tolerance and low temperature-dependence," To be published in Proc. of 2003 IEEE/LEOS International Conf. on Optical MEMS 2003, Hawaii, USA, Aug. 18-21, 2003.), and there is the other approach that is using a reflective micro-mirror with

in-plane motion capability and in-plane light path configuration. This kind of in-plane light path approach based on using taper-ended fibers has been disclosed by C.-H. Kim, Namkyoo Park, and Y.-K. Kim, " MEMS Reflective Type Variable Optical Attenuator Using Off-Axis Misalignment," Proceedings of 2002 IEEE/LEOS International Conf. on **Optical MEMS 2002**, Lugano, Switzerland, Aug. 20-23, 2002, pp. 55-56. By using the taper-ended fibers as the input and output ports, approach of C.-H. Kim et al can make the reflective micro-mirror only need to move very short distance range, let say about several micrometers, due to the spacing between taper-ended fibers is very small. However, the result regarding to optical performance reported by them is not very promising, insertion loss is around 1.8dB which is larger than the normal acceptable value, i.e., less than 1dB, for practical use purpose. At the same time, one of present inventor has presented our invented VOA device based on reflective micro-mirror with in-plane motion capability and in-plane light path configuration approach. (Chengkuo Lee " Challenges in Optical MEMS Commercialization and MEMS Foundry", Presentation materials of invited talk in 2002 IEEE/LEOS International Conf. on **Optical MEMS 2002**, Lugano, Switzerland, Aug. 20-23, 2002) In our approach, we use the lens fibers or collimators to get larger collimated light beam size, and thereby, the general

optical performance of VOA becomes better. But the trade-off is that the micro-mirror actuation distance has to be enlarged in order to fully reflect the incoming light with respect to the beam size. By using the comb drive actuator with said springs disclosed in this invention, we are able to fulfill the need of enlarged micro-mirror actuation distance when we use said reflective micro-mirror and in-plane light path design approach.

Additionally, by integrated multiple reflective mirrors with multiple output ports, the incoming optical signals from one signal port can be reflected and coupled into a specified channel among said output ports. This design is an approach to 1xN optical switch device that was disclosed by J. H. Jerman, J. D. Grade, and J. D. Drake, US Pat. 5993906, "Electrostatic microactuator and method for use thereof," Dec. 7, 1999.

Obviously, using the ideas disclosed in former embodiments, our invented micro-optical devices using electrostatically operated comb drive actuator with enlarged displacement and enlarged force output in conjunction with said reflective micro-mirror and in-plane light path scheme is very promising in said VOA and optical switch applications practically. Some updated result regarding to our invented device can be referred to the following publications. (Chihchung Chen, Chengkuo Lee, Yenjyh Lai, and Wen-Chih Chen,

"Development and Application of Lateral Comb-drive Actuator," Jpn. J. Appl. Phys. Vol. 42, Part.1, No. 6B, 2003, pp.4059-4062; Chihchung Chen, Chengkuo Lee, and Yen-jyh Lai "Novel VOA Using In-Plane Reflective Micromirror and Off-Axis Light Attenuation", IEEE Communications Mag., the quarterly supplement IEEE Optical Communications, pp. S16-S20, Aug. 2003.) In according to the other aspect of our invention, we proposed micro-optical devices as shown in Fig. 11a, the micro-mirror 1111 of said micro-optical device are located and aligned in a geometric layout configuration where the input light beam from the transmission fiber 1114 of input channels reflected by said micro-mirror 1111 toward the reception fiber 1115 of the output channels; thereby the input optical signals according to light path 1112 from the input fiber 1114 is reflected by said micro-mirror 1111 regarding to spatial position at micro-mirror position 1111a toward the reception fiber 1115 according to a light path 1113a, then all the incoming light has been reflected and coupled into the reception fiber 1115. Besides, the input optical signals according to light path 1112 from the input fiber 1114 is reflected by said micro-mirror 1111 regarding to spatial position at micro-mirror position 1111b toward the reception fiber 1115 according to a light path 1113b, then a portion of the incoming light has been reflected and has

not been coupled into the reception fiber 1115, thereafter the uncoupled portion of incoming light is attenuated without back-reflected into the input fiber 1114. By using fiber optics with larger collimated light beam size and actuator with larger displacement, we can reach better optical performance for said micro-optical devices according to present disclosed approach.

On the other hand, regarding to the micro-optical devices, we may integrated or assembled a plurality of reflective micro-mirror together with multiple input and output channels in a device configuration that the micro-mirrors 1151 and 1152 of said micro-optical device are located and aligned in a geometric layout configuration where the input light beam from the transmission fiber 1155 of one of input channels reflected by said micro-mirror 1151 toward another reflective micro-mirror 1152 then being reflected again and transmitted forward to the reception fiber 1156 of the output channels; thereby the input optical signals according to light path 1153 from the input fiber 1155 is reflected by multiple micro-mirrors 1151, 1152, etc. regarding to various spatial position at micro-mirror position 1151a, b and 1152a, b toward the the reception fiber 1156 of the output channels. As a result, By maintaining the micro-mirror 1151 at mirror position 1151a, we may adjust the mirror position regarding to another micro-mirror 1152 from 1154a position to 1154b

position. Moreover, our approach may have broaden adjustable range of light path, say from 1153 input light path to 1154a, 1154b, and 1154c output light path, by using more than one movable reflective micro-mirrors to change the reflected light path. By doing so, we may apply said micro-optical devices for optical switching and variable optical attenuation applications in multiple channels manner, while the good optical performance can be achieved based on our proposed new comb drive actuator designs. Part of this invention has been disclosed in the literatures of: Interactive multimedia materials shown in : Chihchung Chen, Chengkuo Lee, and Yen-jyh Lai "Novel VOA Using In-Plane Reflective Micromirror and Off-Axis Light Attenuation", IEEE Communications Mag., the quarterly supplement IEEE Optical Communications, pp. S16-S20, Aug. 2003.,[http://www.comsoc.org/ci1/Public/2003/aug/index.html].

The fifth embodiment

In according to another aspect of our invention, the micro-optical device is desirable to have a mechanism to hold said micro-mirror in specified spatial location and position with respect to optical paths without electrical power consumption. As disclosed by M. Lim, R. Fan, and L. Que, US. Pat. US

6549107, "Latching mechanism for MEMS actuator and method of fabrication," Apr. 15, 2003, movable arms can enter the spacing of stoppers of shuttle beam with shaped stoppers to hold the shuttle beam at various positions without electrical power consumption. Unlike the aforementioned buckle beam latch mechanism behaving bi-stable motion, this approach can maintain the shuttle beam at as many as positions equivalent to the number of spacing between two shaped stoppers among whole group of shaped stoppers along with the shuttle beam, thereby achieving digitally control of shuttle beam positions.

Regarding to our invention, we propose a new latch, i.e., a clip type latch, mechanism for said micro-optical devices in an analog controllable manner. As shown in shown in Fig. 12 a, a clip type latch mechanism comprises a grip structure 1202 formed on a substrate of said micro-optical device to clamp said shuttle beam 1206 via the friction force forming at the contact interface of the clamped location between grip structure 1202 and shuttle beam 1206; thereby said micro-optical device can maintain its status at states with respect to various micro-mirror 1207 positions and locations in an analog controllable manner without electrical power consumption when said clip type latch is used to clamp said shuttle beam 1206. The grip structure 1202 can be moved by

various micro-actuators 1203. To move and control the micro-mirror 1207 to the desired position is done by the micro-actuators and suspended springs 1201 of said micro-optical device. When the micro-mirror 1207 is moved to said desired position already, we can apply the grip structure 1202 to clamp the shuttle beam 1206. Thereafter, without continuously apply electrical load to said micro-optical device, we may hold said micro-mirror 1207 at desired position with electrical power consumption. As shown in Fig. 12b, the control of grip structure 1252 can also be realized by a micro-actuator 1253, in stead of two micro-actuators 1203 for individually controlling the grip structure 1202 shown in Fig. 12a. Additionally, if we separate two sides of the grip structure 1202 in Fig. 12a or 1252 in Fig. 12b into two electrical electrodes with a voltage difference, and there is insulation coating on the contacting surface of 1202 and 1252, then the grip arms from two sides of grip structure can move close to each other due to the electrostatic force, and shuttle beam 1206 in Fig. 12a or 1256 in Fig. 12b will be clamped by these two grip arms 1202 in Fig. 12a or 1252 in Fig. 12b, respectively, due to said electrostatic force. Briefly speaking, clip type latches by using friction force or electrostatic force are invented for said micro-optical devices to maintain the status of said micro-optical devices at certain condition without power consumption in an

analog control manner.

The sixth embodiment

According to the present invention, many ways can be provided to make the mirror surface smoothness of said micro-optical devices in a mass production manner with higher production yield. Basically the following approaches have been reported to exhibit the result to make a silicon side wall surface the same as the facet planes regarding to single crystal silicon, such as, applying the silicon etching solution, such as the KOH or TMAH solution to reduce the surface roughness, and adopting the (110) oriented silicon substrate in conjunction with post-etching in the silicon etching solution. (See for example, M. Sasaki, T. Fujii, Y. Li, and K. Hane, "Anisotropic Si Etching Technique for Optically Smooth Surface," IEEE Proceedings of Transducers'01, the 11th international conference on solid-state sensors and actuators, Munich, Germany, June 10-14, 2001.) Besides, we can also oxidize the mirror surface after the mirror sidewall is formed by DRIE, then certain level of surface corrugated silicon microstructures will become SiO2. After removing the SiO2, we can have very smooth silicon mirror with optical level of quality. We had applied these kinds of approaches to make micro-mirror of said micro-optical devices become very smooth. Part of the relative results have been published by Chihchung Chen, Chengkuo Lee, and Yen-jyh Lai "Novel VOA Using In-Plane Reflective Micromirror and Off-Axis Light Attenuation", IEEE Communications Mag., the quarterly supplement IEEE Optical Communications, pp. S16-S20, Aug. 2003.

According to the other aspect of present invention, we also apply many ways can be provided to make the packaging process of said micro-optical

devices in a mass production manner with higher production yield, such as using the lid capping on the substrate to protect the fragile MEMS elements; making flow channels and trenches on the substrate to avoid the movable and suspended MEMS elements being attacked by the sealing and assembling materials like glues, epoxy, solders, etc; and dicing the devices form substrates, then became discrete dies when the MEMS elements have been protected by lids.

While the description above provides a full and complete disclosure of the preferred embodiments of the present invention, various modifications, alternatives, and equivalents will be obvious to those of skill in the art. Accordingly, the scope of the invention is limited solely by the following claims.